OTR Imaging Considerations for ILC-TA at NML

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ABSTRACT

Optical transition radiation (OTR) imaging is planned as a minimally intercepting beam-size monitor for the electron beams in the ILC-TA NML facility at FNAL. Practically the technique would be used for the lower-charge test macropulses at 570-750 MeV. Considerations of expected beam emittance and lattice functions are used to evaluate the expected beam sizes at the OTR stations and to project reasonable design goals of the imaging systems. Since the beam sizes expected would be $\sigma \geq 160$ μm for $\beta \geq 2$ m and $\varepsilon_n = 25$ pi mm mrad (following compression), standard analog or digital CCD cameras with normal optics solutions are operationally reasonable for all stations.

INTRODUCTION

A GeV-class superconducting rf (SCRF) linear accelerator is under construction at the New Muon Laboratory (NML) building at Fermilab [1]. This will serve as a test accelerator for the International Linear Collider (ILC) SCRF technology and other beam physics or diagnostics issues. Characterization of the electron beams will be an important aspect of the ILC-TA project. Beam size, position, divergence, emittance, and bunch length measurements are of interest, and all of these parameters can be assessed by imaging techniques based on optical transition radiation (OTR) as shown in the past [2-4]. Minimally intercepting beam profile monitors based on OTR are being planned for the downstream beamline following the cryomodules where beam energies of 570 to 750 MeV are initially projected. Additional cryounits may be added to bring the final energy up to 1500 to 1800 MeV. The OTR stations are envisioned for use with test macropulses of perhaps 1-30 micropulses with 1 to 3 nC each. Thin metal converter screens of a few microns in thickness or Al-coated substrates of low z materials are possible options. These screens would *not* be used for the full power macropulse with 3000 micropulses of up to 3 nC each with a macropulse rate of 5 Hz unless the areal charge density is below the foil-damage threshold. A separate report described the proposed use of optical diffraction radiation (ODR) imaging as a nonintercepting (NI) beam-size monitor for the high-power mode [5].

The main purpose of this report is to assess the expected beam sizes for the charge, emittances, and lattice configurations of ILC-TA and to define the imaging system specifications. The nominal normalized rms emittances for the Zeuthen PC gun are 4.5 π mm mrad in both planes at 3 nC per micropulse. At the present time, simulations indicate that full bunch compression at 40 MeV will result in the emittance growth to about 25 π mm mrad [6]. Thus for the general ILC-TA beam-compressed mode and $\beta \geq 2$ m one would expect beam sizes of about $\sigma \geq 160$ μm at 750 MeV. Since the beta functions are larger than this at all OTR stations except one, even larger beam sizes would result, and we expect standard imaging practices can be employed.

BACKGROUND

ANALYTICAL MODEL CONSIDERATIONS

For completeness some background on OTR is included. Our strategy is to convert particle beam information to visible radiation and then take advantage of imaging technology and image processing programs. OTR is emitted when a charged particle beam transits the interface between different dielectric constants. The effect is a surface phenomenon that can be understood as the collapsing of the electric dipole formed by the approaching beam charge and its image charge in the material at the surface. The radiation is emitted promptly in the order of tens of fs and is broadband including the visible spectrum. Using the formalism from Ref. [4] for coherent OTRI calculations as a starting point, we can still apply it to the incoherent case where the coherence function simplifies to just *N*, the number of particles. The general relationship for the number of photons per unit frequency interval and solid angle is given by a product of several functions in Eq. 1 [4]:

$$\frac{d^2N}{d\omega d\Omega} = \left|r_{\perp,\parallel}\right|^2 \frac{d^2N_1}{d\omega d\Omega} I(\boldsymbol{k})\mathcal{F}(\boldsymbol{k}) \qquad (1)$$

where the reflection coefficients *r* are indicated; the single electron OTR spectral angular distribution is

$$\frac{d^2N_1}{d\omega d\Omega} = \frac{e^2}{\hbar c}\frac{1}{\pi^2\omega}\frac{\left(\theta_x^2+\theta_y^2\right)}{\left(\gamma^{-2}+\theta_x^2+\theta_y^2\right)^2}, \qquad (2)$$

where θ_x and θ_y are measured with respect to the angle of specular reflection; γ is the Lorentz factor; $I(\boldsymbol{k})$ is the interference term; and $\mathcal{F}(\boldsymbol{k})$ is the coherence function; and $I(\boldsymbol{k})$ is given by

$$I(\boldsymbol{k}) = 4\sin^2\left[\frac{kL}{4}\left(\gamma^{-2}+\theta_x^2+\theta_y^2\right)\right], \qquad (3)$$

where L = foil separation and $\boldsymbol{k}$ is the wave vector.

Typically for $\gamma = 100$, one photon per 10^3 charged particles is generated in the visible light band over all OTR angles. So, one key to an intense image is, of course, intense particle beams. In recent experiments at the Advanced Photon Source (APS) with electron beams we had 10^9 particles, but the ILC-TA full macropulse has beam intensities projected in the 10^{12} to 10^{13} range. The other key is to have γ large enough so that the peak intensity of emissions at an opening angle of $1/\gamma$ can allow efficient collection of the radiation cone. As an example we show a schematic in Fig. 1a of the OTR angular distribution pattern expected from Eq. 2. This is for a lower gamma case of 80, but the features are representative of the physics and also of the beam before the cryomodules. The opening angle and spectral dependence are indicated. In principle, the beam divergences can be convolved with the single-electron function to provide a divergence measurement [7-9]. If the divergence value is about $1/\gamma$, the central minimum of the pattern will be filled in completely. In ILC-TA, for the 500-MeV electrons we have $\gamma \sim 1000$, and the opening angle is about 1 mrad. A 50-mm diameter lens at 1 meter is more than adequate to collect the radiation cone of about $4/\gamma$. (This would be marginal at γ = 80.) We use the backward OTR so the reflection coefficient of the material is involved. In this case “shiny” is better. The beam size distribution is seen in the image plane and the far-field angular distribution is seen at the focal plane as schematically shown in Fig. 1b. By changing the lens-to-CCD-sensor separation via remote control, we could select the optical configuration. The primary mode is focus at the object for ILC-TA operations, but there are some conditions of low β function values with high emittance when the single-foil angular distribution would be sufficiently sensitive to beam divergence for useful measurements. This option might only be used in the beam-waist area.

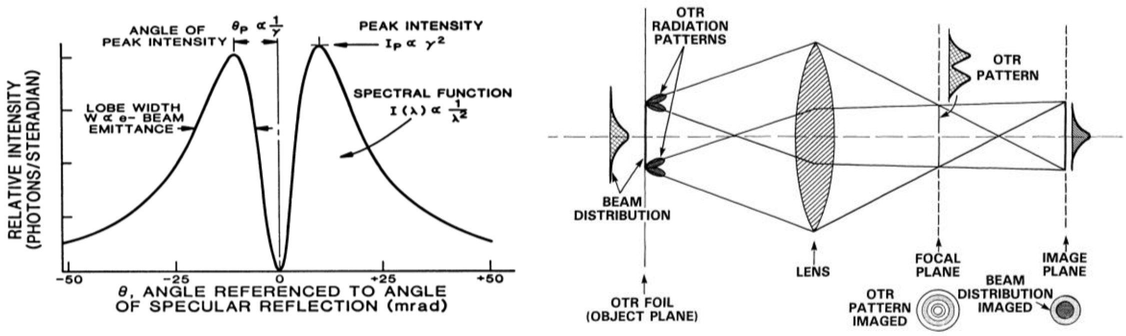

Fig. 1. Schematic of a) the OTR angular distribution features and parameter dependencies for γ = 80 and b) the object-plane focus for beam profile imaging and the focus-at-infinity mode for angular-distribution imaging.

An example image of a 7-GeV electron-beam micropulse of only 0.4 nC charge is shown in Fig. 2. The vertical and horizontal beam size sigmas of 200 and 1375 µm, respectively, bracket most of the expected ILC-TA cases. The y calibration factor is about 45 µm per pixel in this case. The OTR source strength will be reduced at lower gamma.

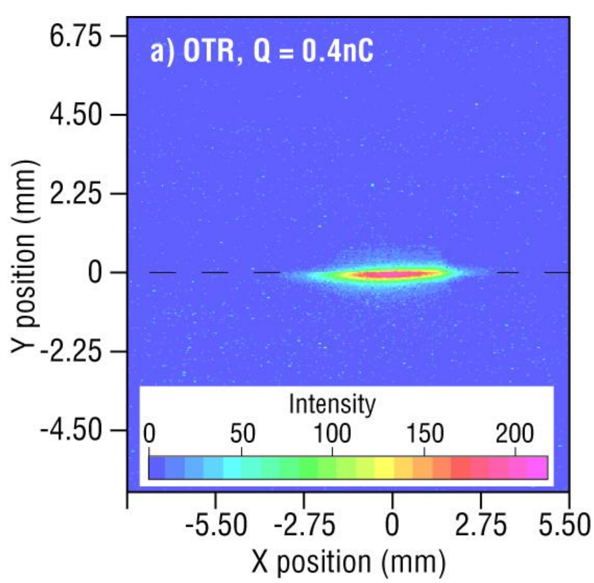

Fig. 2. Results of near-field imaging tests at 7 GeV at APS. The OTR image with beam size about 1375 µm by 200 µm for x and y, respectively, was obtained with one micropulse of 0.4 nC and a standard CCD camera. The horizontal dashed line represents the vertical centerline position.

OPTICAL CALIBRATION LAB OPTIONS

The basic parameters for the imaging system include resolution, calibration factor, field-of-view (FOV), and sensitivity. As an illustrative example, we include the results of calibrations done on a Roper Scientific 16-bit ICCD camera combined with an 105-mm Nikon zoom lens at the APS S35 optics lab earlier this year [10]. This sensitive camera is not needed for normal OTR beam-size imaging, but may be relevant to OTR interferometry or ODR near- or far-field imaging [5].

The camera was mounted on a rail with carriers so the 105-mm F-mount Nikon zoom lens could be used at different working distances. The calibration lab has a platform holding a filter wheel that includes a back-illuminated 15-µm diameter pinhole as a resolution test object and a grid pattern for spatial calibrations. The platform can be moved in three dimensions under computer control for centering the source or scanning the field of view and for precise z-motion relative to the camera lens distance to optimal focus. A photograph of the setup is shown in Fig. 3.

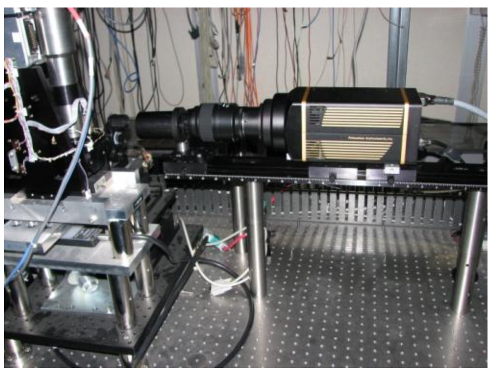

Figure 3: Photograph of the ICCD camera on the S35 optical calibration table. Calibration factors and resolution tests were obtained for various lens working distances.

The tests were initially done at working distances of 14 cm, 17.3 cm, and 29 cm. The grid pattern was used to obtain the calibration factor in each case. A bright square, 10 mm on each side, was used as the main reference. Fine features in the pattern were used for initial focus adjustments. We then selected the pinhole source and scanned the z direction over several mm. An example of the preliminary depth-of-focus results for a working distance of 17.3 cm is shown in Fig. 4, where the FWHM resolution is 2.5 ch or 50 µm.

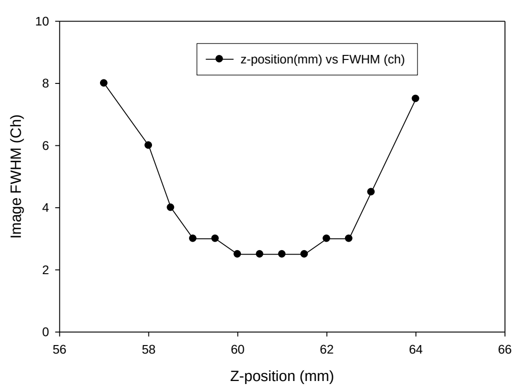

Figure 4. Depth-of-focus scan for a working distance of 17.3 cm for the 105-mm lens. The 2.5 ch (FWHM) resolution would be 50 µm for this calibration factor.

These data show that for this lens setting, resolution can be degraded if the z position is off by 3 mm from the center of the focus curve. Additional working distances were used at 40, 50, 60, and 70 cm, but the resolution test was not done because we had consistently obtained the 2.5-ch FWHM result, just with different calibration factors. The calibration factors and expected FOV are shown in Table 1. This table illustrates the type of trades one must consider in setting specifications.

Table 1: Summary of the Calibration Factors and FOVs with the 105-mm zoom lens and several Working Distances.

Working Distance (cm)	Calibration Factor (μm/pixel)	FOV (cm)
14.0	13.7	1.4
17.3	19.6	2.0
29.0	36.9	3.8
40.0	50.0	5.1
50.0	62.5	6.3
60.0	74.0	7.6
70.0	89.3	9.1

ILC-TA APPLICATION

Beam sizes for the baseline ILC-TA facility at the downstream beamline locations can be estimated from the expected beam emittance and the lattice functions. For example, if the emittance is indeed degraded by the bunch compression process from 4.5 to ~25 pi mm mrad and with the beta function of 2 m, one would expect at 750 MeV beam-size sigmas of ~160 μm. In general, the basic OTR station with a stepper motor drive or pneumatic actuator would be adequate for all stations, with the stepper motor for those with an ODR function. A filter wheel(s) or other device to select ND filters, bandpass filters, and two polarizers should be included. In Figs. 4 and 5 the OTR stations in the diagnostics section and the test area are indicated in the latter by vertical arrows. We will consider these locations as 1-7 from left to right. The expected beam size sigmas are shown in Tables 2-4, Row 4 for the emittance value and the range of β function values listed.

Operationally, one could use the three-station configuration (5,6,7) in the test area to provide an emittance monitor independent of the beta function determination. A beam waist generated at the center screen with adequate drift either way would simplify the emittance calculation. The lattice functions for 570 MeV are provided in Fig. 5 for the downstream beamline for completeness. In this case (#2) the beta functions are 12 m in both planes on either end of the 3-m drift and 0.2 m at the waist with the center at about z = 11 m. The expected beam sizes for the high-emittance case would be 520 μm and 70 μm, respectively, with about $5^{1/2}$ times smaller beam sizes in the low-emittance case. The waist beam size would then approach the beam sizes expected in the ILC main linac [11]. N.B. It would simplify the imaging designs, if beta functions at the waist would be kept at the 2 m level or larger if the low-emittance mode is used. Far-field imaging could be evaluated for complementary divergence measurements. Single-foil sensitivity would be reasonable down to values about 10% of 1/γ. Depending on the actual beam sizes and the screen thickness, signals from a number of micropulses at the 3 MHz rate can be integrated to assess beam size. These screens would not be inserted at full macropulse charge, but hopefully there could be a lower charge that could be used as an overlap point with the ODR data.

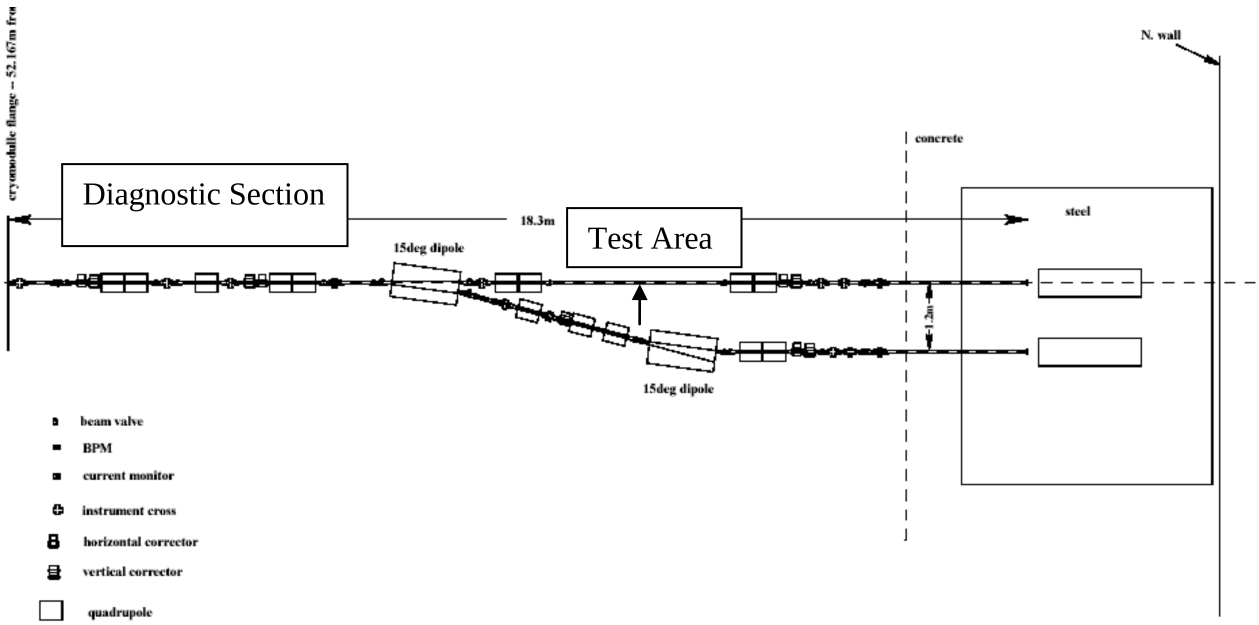

Fig. 4. Schematic of the NML Downstream Beamline with diagnostic section and test area indicated (courtesy of Mike Church, 8/23/07).

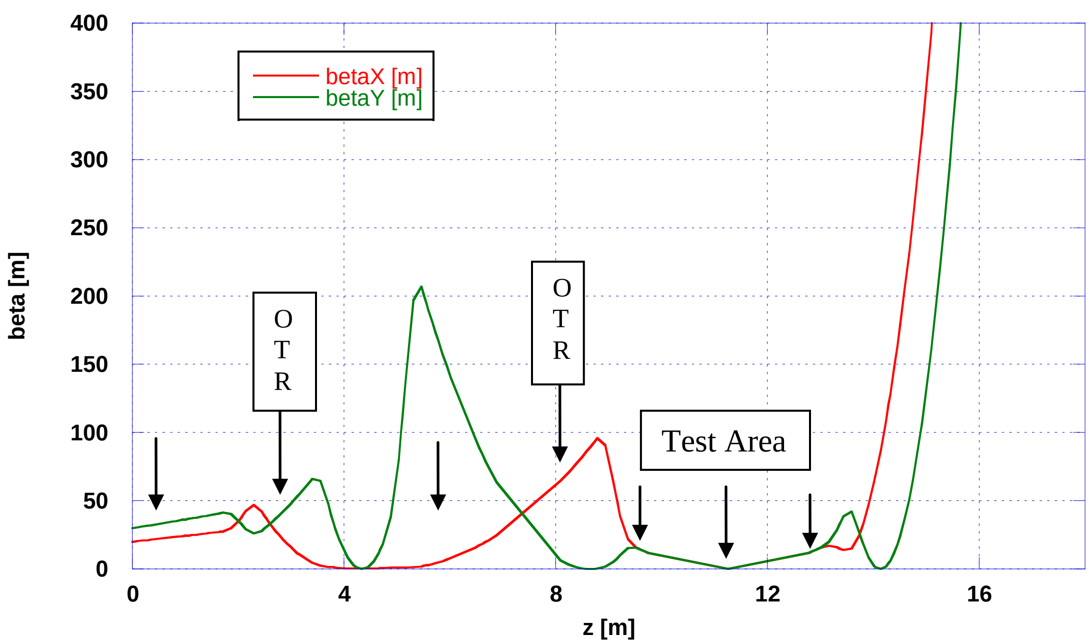

Fig. 5. Lattice functions (case 2 waist at z~11 m) for the NML Downstream beamline with the seven proposed OTR stations including the three-station configuration in the test area indicated by the vertical arrows (lattice plot courtesy of Mike Church, 8/22/07).

Table 2: ILC-TA parameters for the downstream OTR locations 1-4.

Parameter	Nominal Value	Range	Resolution	Bandwidth	Technique
Energy (MeV)	570	500-750	0.1	5 Hz	Spectrometer
Charge/micro (nC)	3	0.5-4	0.1	5 Hz	FCT
Micropulse No. @ 3 MHz, 5Hz	1	1-30	1	5 Hz	
Beam size σ (μm)	670,820	200-2000	50	5 Hz	Image, CCD
Divergence (mrad)	0.09	0.05-0.20			Quad. field scan, CCD
Norm.Emittance (π mm mrad)	25	20-30	0.5	5 Hz	Calculate
$\beta_{x,y}$ (m)	20,30	2-200	5%		
Bunch Length (rms ps)	2	1-5	0.6	5 Hz	Streak cam., E-O, CTR
Beam position	Centerline	+-5 mm	0.1 mm	5 Hz	rf BPM, CCD
Macropulse rate	5 Hz				

Table 3: ILC-TA downstream beamline parameters for OTR locations 5,7.

Parameter	Nominal Value	Range	Resolution	Bandwidth	Technique
Energy (MeV)	570	500-750	0.1	5 Hz	Spectrometer
Charge/micro (nC)	3	0.5-4	0.1	5 Hz	FCT
Micropulse No. @ 3 MHz, 5Hz	1	1-30	1	5 Hz	
Beam size σ (μm)	520	200-1500	50	5 Hz	Image, CCD
Divergence (mrad)	0.09	0.05-0.20			Quad. field scan, CCD
Norm.Emittance (π mm mrad)	25	20-30	0.5	5 Hz	Calculate
$\beta_{x,y}$ (m)	12,12	2-100	5%		
Bunch Length (rms ps)	2	1-5	0.6	5 Hz	Streak cam., E-O, CTR
Beam position	Centerline	+-5 mm	0.1 mm	5 Hz	rf BPM, CCD

Table 4: ILC-TA parameters for the downstream beamline location 6 (waist).

Parameter	Nominal Value	Range	Resolution	Bandwidth	Technique
Energy (MeV)	570	500-750	0.1	5 Hz	Spectrometer
Charge/micro (nC)	3	0.5-4	0.1	5 Hz	FCT
Micropulse No. @ 3 MHz, 5Hz	1	1-30	1	5 Hz	
Beam size σ (μm)	70	70-500	20	5 Hz	Image, CCD
Divergence (mrad)	0.09	0.05-0.20			Quad. field scan, CCD
Norm.Emittance (π mm mrad)	25	20-30	0.5	5 Hz	Calculate
$\beta_{x,y}$ (m)	0.2,0.2	0.2-10	5%		
Bunch Length (rms ps)	2	1-5	0.6	5 Hz	Streak cam., E-O, CTR
Beam position	Centerline	+-5 mm	0.1 mm	5 Hz	rf BPM, CCD

For bunch-compressed, high-charge-per-micropulse conditions, optical magnifications that provide 50-μm rms resolution with a 20-mm FOV are proposed for stations 1-7, except for station 6 which would need 20-μm rms resolution with a FOV of 6-8 mm.

If the low-emittance mode of 4.5 π mm mrad is used, the expected beam sizes will scale down by $5^{1/2}$. The beta functions should be kept at 2 m or above so the proscribed resolutions are still sufficient. Currently, the low-emittance mode is not an expected ILC-TA operational mode as I understand it. Special run modes should be assessed as relevant. For example, if low charge per micropulse (<1 nC) with no compression is selected, the emittance could approach 1.5 π mm mrad. The beam sizes would dictate a higher resolution optics configuration at the OTR location 6 if low β values are used for this special case. Also for the extreme range of energies of 200 MeV running the rf off crest and 1800 MeV with 2 rf units, the beta functions would be adjusted accordingly to stay in the target beam-size range.

SUMMARY

In summary, the baseline ILC-TA diagnostics plans include the implementation of OTR imaging stations in the downstream beam line. For bunch-compressed, high charge per micropulse conditions, optical magnifications that provide 50-μm rms resolution with a 20-mm FOV are proposed for stations 1-7, except for station 6 which requires better resolution as described. It appears that if the β functions are kept at 2 m or larger, even the low-emittance beams will be imaged properly with these manageable resolutions.

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